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Paper Session II-B - Smarter Software for Enhanced Vehicle Health Monitoring and Inter-Planetary Exploration

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Abstract

The existing philosophy for space mission control was born in the early days of the space program when technology did not exist to put significant control responsibility onboard the spacecraft. NASA relied on a team of ground control experts to troubleshoot systems when problems occurred. As computing capability improved, more responsibility was handed over to the systems software. However, there is still a large contingent of both launch and flight controllers supporting each mission. New technology can update this philosophy to increase mission assurance and reduce the cost of inter-planetary exploration.

The advent of model-based diagnosis and intelligent planning software enables spacecraft to handle most routine problems automatically and allocate resources in a flexible way to realize mission objectives. The manifests for recent missions include multiple subsystems and complex experiments. Spacecraft must operate at longer distances from earth where communications delays make earthbound command and control impractical.

NASA's Ames Research Center (ARC) has demonstrated the utility of onboard diagnosis and planning with the Remote Agent experiment in 1999. KSC has pioneered model-based diagnosis and demonstrated its utility for ground support operations. KSC and ARC are cooperating in research to improve the state of the art of this technology. This paper highlights model-based reasoning applications for Moon and Mars missions including in-situ resource utilization and enhanced vehicle health monitoring.

Introduction

For as long as mankind has existed, we have looked to the heavens and wondered what was out there. Early astrologers charted the stars in an effort to unveil the future. As we continued our study of the skies we learned that those points of light were Suns, many like our own; and we began to speculate about the possibility of life beyond the Earth. For thousands of years answers to those questions were beyond our reach. But at the dawn of the 21st Century we are beginning to take positive steps towards the answer to this most fundamental question. New techniques in astronomy have confirmed the existence of other planets in the Milky Way Galaxy. But these discoveries are just tantalizing clues about the possibility of life beyond Earth. And these remote planets are still beyond our grasp. The search for life in the Universe must begin closer to home.

Of all the planets in our solar system, Mars has long been the focus of our attentions. Astronomers Giovanni Schiaparelli and Percival Lowell believed that they saw canals crossing the face or Mars. (See Figure 1) This led the imagination of mankind to speculate about a race struggling to survive on a dying planet. While better telescopes disproved the canal theory, recent evidence from NASA suggests that Mars may have once had (or may still have) the ingredients necessary for life. Pictures from the Mars Global Surveyor suggest the possibility of water flows in the recent geological past. (Figure 2) A couple of Martian meteorites appear to have fossilized bacteria in them. (Figure 3) The Nakhla Meteorite, in a recent study sponsored by

Arizona State University, hints at a possible salty ocean. The only way we will answer these questions is to explore the surface extensively.

Paleontologists such as Charles D. Wolcott (Figure 4) have spent extraordinary time and effort in the wastelands of the Earth searching for fossils. To think that we can find evidence of past life on Mars by sampling a few sites with robotic landers is questionable. Interestingly enough, Wolcott was the first director of National Advisory Committee for Aeronautics (NACA) the precursor to NASA. He spent more than 50 years collecting fossils all over North America. The only way to answer the questions about Mars is to send humans to the planet for extended periods of time. NASA is now developing the technologies that will enable human exploration at an affordable cost.

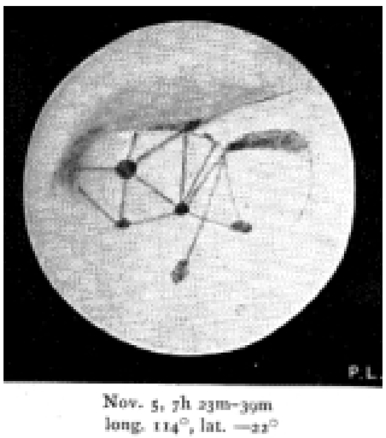

Figure 1 - Mars Observation by Lowell

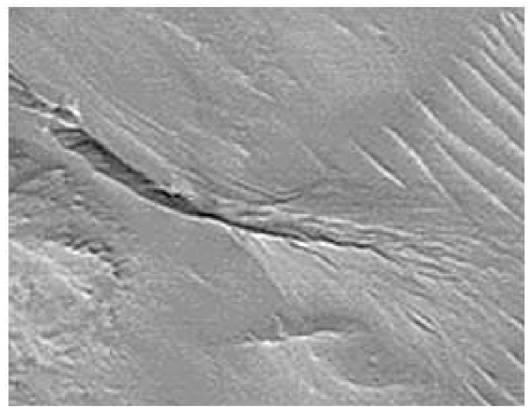

Figure 2 - Evidence of Recent Water Flows on Mars – (NASA/JPL)

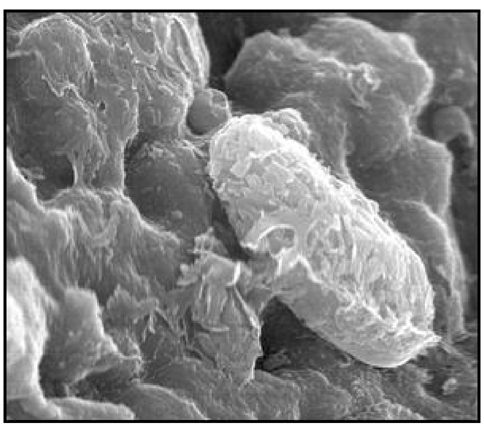

Figure 3 - Fossilized Bacteria (NASA/JSC)

Figure 4 – Paleontologist and NASA forefather Charles D. Walcott

Enabling a Vision

NASA has had brute force technology available for the exploration of Mars for a number of years. Unfortunately, the cost of an Apollo-styled Mars mission would be extraordinary. In 1989, President Bush made a call on the 20th anniversary of the first Moon landing for the Nation to return to the Moon and press onward to Mars. The plan that NASA presented to Congress cost 450 billion dollars. As one might expect, the plan was Dead On Arrival! The plan may have been dead, but the dream remained alive.

To drive down the cost and increase the safety of a human Mars mission, a fundamental change in the philosophy of space mission control is required. The existing philosophy was born in the early days of the space program. In the late 50's, the technology did not exist to place a significant share of the control responsibility in the systems software. In addition, the embedded analog controllers were crude by today's standards. So NASA relied on a team of ground control experts. Figure 5 shows the conceptual control systems architecture used by NASA Space missions[1]. The ground controllers monitor telemetry from the spacecraft. When a problem is discovered, the controllers use their systems engineering expertise to identify the probable cause and propose a solution. This basic architecture has changed little in the 40 years since the dawn of human space flight.

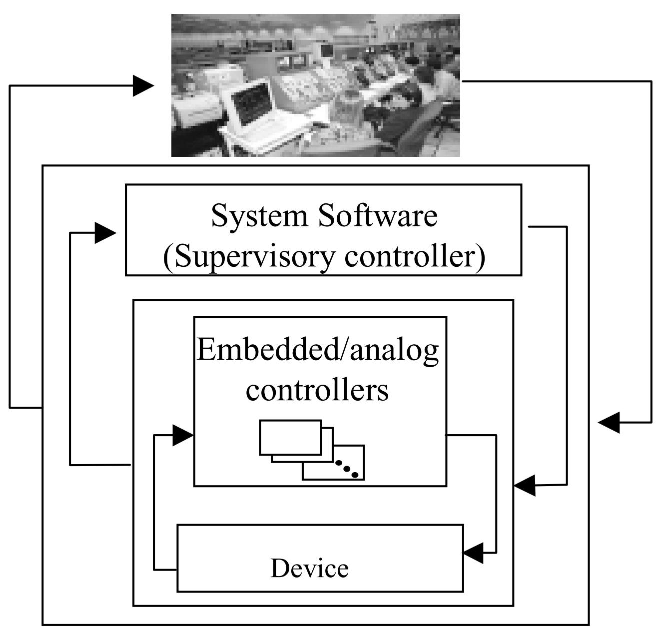

Figure 5 - Control Architecture Based on Ground Experts

Today's Software Still Requires Too Much Human Intervention

What has changed is the ability of computer hardware and software to bear a greater responsibility for spacecraft control and configuration. As each generation of spacecraft has evolved, more and more capability has been added to both the embedded controllers and the systems software. Systems software in the Space Shuttle makes many critical real-time decisions throughout the mission. A significant example of this capability came recently on the launch of STS-93. An electrical short caused a momentary power dropout on one of the two main power buses. This shut down one of two redundant main engine controllers. Due to the sophistication of the system software, the Shuttle computers quickly selected the backup controller and the mission was completed successfully. Although the sophistication of today's space vehicle system software is impressive, it still relies upon a room full of ground controllers to monitor the flight on a continuous basis. This has always been very expensive, but missions have typically lasted only two weeks. A human Mars mission based on the current reference mission could last over two years. Not only would this be exorbitantly expensive, it is also impractical due to the distances involved.

The human space program has always had the luxury of almost continuous communications between the vehicle and the ground. For years NASA maintained a ground station network throughout the world so that the astronauts were never without help from the ground. The first time that a communications blackout occurred was during the Apollo program when the astronaut's trajectory carried them to the far side of the moon. Due to their close proximity to Earth, all time delays resulting from the distance involved were minimal. Again, Apollo was the worst-case scenario to date, and that communications delay was only 3 seconds. Humans on the surface of Mars will experience telemetry and communications delays of 20 minutes or more. In some cases communications will be impossible due to interference from the Sun. This blackout, caused by planetary alignment, can last up to two weeks.

A New Paradigm for Mission Control

Clearly, the systems software must take on added responsibility for the identification and resolution of problems. This software must have the same systems knowledge that today's ground controllers possess. It must not only have the ability to detect straightforward failures like the Shuttle power glitch mentioned above. It must also be able to reason about nuances of system degradation. It must also detect erroneous sensor readings that might indicate a supposed problem where none truly exists.

Intelligent Systems Software will have wide ranging impacts on all areas of a Mars mission. It can be used in continuous process systems like the environmental control system, wastewater regeneration, power generation and In-Situ Resource Utilization (ISRU).

Kennedy Space Center (KSC) has invested in the development of model-based diagnosis and control applications for sixteen years having broad experience in both ground and spacecraft systems and software. KSC has now partnered with Ames Research Center (ARC), NASA's Center of Excellence in Information Technology, to create a new paradigm for the control of dynamic space systems. ARC has developed model-based diagnosis and intelligent planning software that enables spacecraft to handle most routine problems automatically and allocate resources in a flexible way to realize mission objectives. ARC demonstrated the utility of onboard diagnosis and planning with an experiment aboard Deep Space 1 in 1999. Deep Space One was created to test out a series of new technologies from ion propulsion to autonomous spacecraft navigation. KSC is now working with ARC to extend this technology into the realm of chemical process control and In-situ Resource Utilization using the Reverse Water Gas Shift (RWGS) testbed.

In-situ Resource Utilization (ISRU)

In-Situ Resource Utilization is an important strategy for NASA's design reference missions[2] and has become a key component of plans to send human crews to Mars. One of the most significant cost factors for Mars exploration is the amount of mass carried to Mars and back. For every kilogram making the round trip, forty (40) kilograms must be lifted to low earth orbit at the beginning of the mission. Major savings can be achieved by making some of the fuel for the return trip from resources available on the Martian surface because the heaviest part of any launch vehicle is the fuel it carries. Furthermore, there are other consumables that are needed in large quantities for a long duration mission, such as Oxygen for breathing. This technology has the potential to significantly reduce the cost and enhance the safety of human Mars missions.

Reverse Water Gas Shift (RWGS)

One of the more promising technologies for ISRU is the Reverse Water Gas Shift (RWGS) process. RWGS is a method for producing Oxygen from the atmosphere of Mars, which is mostly carbon dioxide. The reaction works as follows: carbon dioxide is combined with hydrogen (brought from earth) in the following reaction: $CO_2 + H_2 = H_2O + CO$

The water produced in the RWGS reactor is collected in a condenser and delivered to an electrolyzer. Oxygen produced by electrolysis is stored and the hydrogen is recovered and recirculated into the input stream. (See below Figure 6 - Simplified RWGS Schematic) Since most of the hydrogen is reused, the import requirements from earth are small.

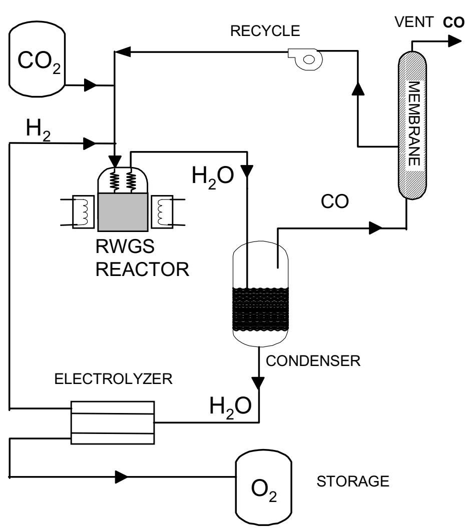

Figure 6 - Simplified RWGS Schematic

Implementing these chemical processes on the Martian surface will take a considerable amount of process engineering. CO_2 must be acquired, compressed and stored. The products of the reaction must be liquefied and stored. Hydrogen for the RWGS process will likely be delivered to the surface as a cryogen and will require processing to supply it as a process gas. The reactions themselves are optimized over a narrow range of temperature and gas composition. Therefore the control system must be able to adjust to variations in operating conditions and equipment health to maintain optimal fuel production rates. These requirements emphasize the need for intelligent systems control.

Autonomous monitoring and control

Current mission profiles call for ISRU systems to operate unattended on the Mars surface for two years or more without human intervention. During such a long period it is certain that some subsystem and measurement failures will occur. Satellites in earth orbit are designed for such lifetimes; but for reasons already discussed, the Mars mission will not enjoy the luxury of round-the-clock human operators who are in constant contact with the vehicle. The task of the autonomous system is to be truly fault-tolerant by taking corrective action without ground intervention. This requires the ability to continuously adapt to degraded sensor environments as well as automated planning for resource and redundancy management.

Autonomous Control of a RWGS System

The RWGS test bed uses Livingstone monitoring and diagnosis software developed at ARC. ARC has been working with KSC to apply Livingstone to ISRU since 1998. The software provides built-in autonomy capabilities for RWGS.

The heart of the RWGS intelligent system is a high-level system model of the test bed written in the Livingstone modeling language. The model is a simple, declarative statement of the behavior of RWGS components and the connections between them. Information from the design of the test bed is simply translated, part-by-part and concept-by-concept into Livingstone statements.

Figure 7 is an example of a valve component model. The engineer has defined finite states for the valve corresponding to various normal and abnormal operating modes. Transitions are defined corresponding to device commands and faults. Logical propositions define the behavior of the valve while it is in the associated mode.

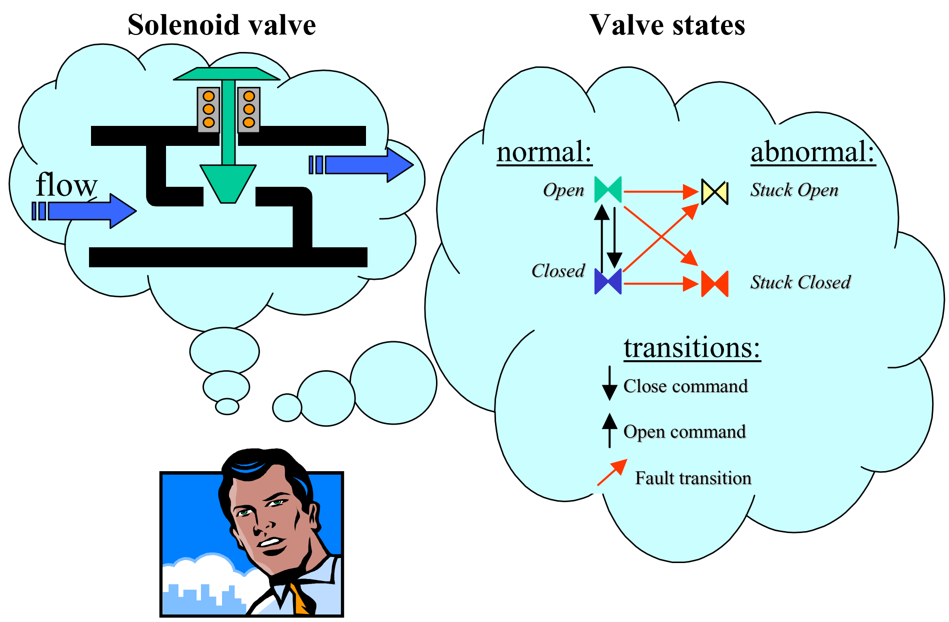

Figure 7 - Valve Component Model

One of the key benefits of this modeling paradigm is that the engineer is only responsible for describing the *local* behavior of each component (Figure 7) and the relationships that exist between components. Livingstone then uses this specification to compose a larger, system model that can be used to reason about the *global* behavior of the entire system given the mode of each component. Once the model is complete and connected to test bed instrumentation, the advisory and autonomy features of the Livingstone engine are available for use. As discussed above, these benefits include system health monitoring, diagnosis of component failures, flexible reconfiguration, redundancy management, adaptability to degraded environments, and tolerance for component faults and incomplete sensor information.

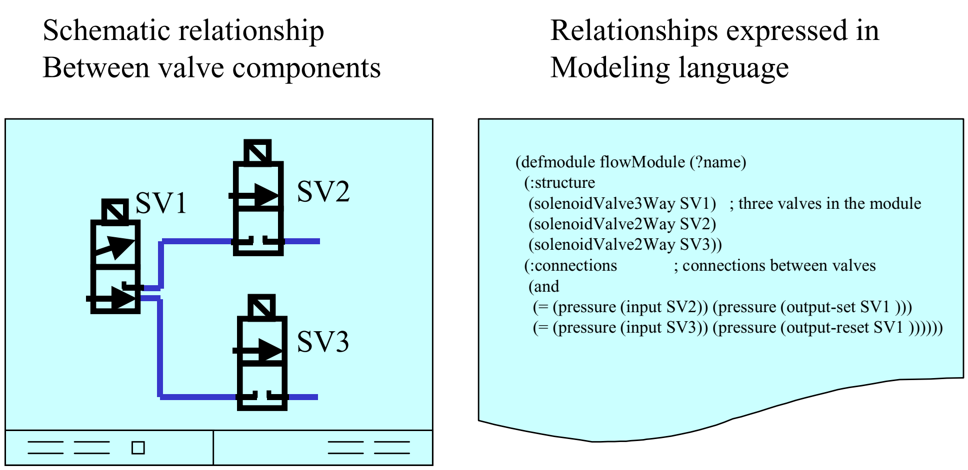

Figure 8 - Defining Relationships Between Components

Benefits of Intelligent Software

The RWGS test bed is designed for unattended operation, and its control system illustrates many features and advantages of intelligent software. Two examples of examples are highlighted below: redundancy management and adaptability to degraded environments

Redundancy Management

One example of component redundancy in RWGS is gas supply valves. As mentioned above, the RWGS mixes two gas streams into a reactor to achieve the desired products. Feed flows from each of these gas sources are connected with redundant components as in Figure 8. Since this redundancy is part of the model, Livingstone is able to reason about how a valve such as SV2 (above) that is stuck closed could cause a low feed rate. Livingstone's system model simulates global behavior of RWGS with a stuck-closed valve. The simulation predicts that this would result in anomalous gas composition ratios. Livingstone automatically compares the predicted compositions with current observations from RWGS measurements and is able to confirm the diagnosis. In addition, the Livingstone engine is capable of manipulating the model to determine whether redundant flow paths exist for restoring nominal flows. In the "Flow Module" of Figure 8, a redundant path *does* exist, and Livingstone is capable of directing the control executive to reset SV1, open the backup valve (SV3) and overcome the fault to continue normal production.

Adapting to Degraded Environments

The principal source of Hydrogen flow in RWGS is the electrolyzer (See Figure 6 above). Flowmeters measure its hydrogen production. An ammeter measures the current flowing in the electrolyzer. By the chemical equation for the electrolysis of water, we know there is a relationship between hydrogen production and electrolyzer current. This makes it possible to use the ammeter as a check on hydrogen flow or to use the flowmeter as a measurement of electrolyzer current. If either measurement malfunctions while in operation on Mars, the other can be used as a backup. The chemical equations for electrolysis are part of the Livingstone model. Livingstone automatically takes advantage of the "logical redundancy" in the RWGS process. Even greater redundancy is available vis-à-vis the electrolyzer since flowmeters also measure the oxygen production rate of the system. The oxygen production rate is related to electrolyzer current by the same chemical equation for water electrolysis. This equation also computes the water consumption of the electrolyzer. Since a level sensor on the RWGS condenser directly measures water use (See Figure 6 above) all four of these measurements can be used to track the others and maintain effective control of various parts of RWGS. This feature greatly enhances mission assurance and makes the RWGS control system extremely robust and fault tolerant. The loss of one or more of these four measurements over the operating life of RWGS will not hinder effective control of the system.

Concluding Remarks

Planetary research in recent decades has made it clear that exploration of Mars is the most feasible alternative for discovering evidence of life beyond Earth. Furthermore, it is apparent that painstaking, human investigation is needed to collect and examine material containing fossils or other evidence of biological interest. NASA is developing intelligent software and ISRU technologies that will make human exploration affordable and feasible. Model-based software using the Livingstone system will enable systems to work autonomously for long periods of time in degraded environments. Computer hardware and software is now able to bear a greater responsibility for fulfilling the vision of exploration of the solar system.

Acknowledgments

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[2] S.J. Hoffman and D.I. Kaplan, editors. Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team. NASA Special Publication 6107, July 1997.